Preface

Φύσις κρύπτεσθαι φιλεῖ

Ἡράκλειτος[*]

This book develops for the first time a complete and connected non-linear theory for the analog Phase-Locked Loop (PLL), which clarifies the obscure points of its complex non-linear behaviour.

The material of the book is divided into six parts. The extensive and tedious mathematic calculations and the experimental results are presented in ten appendices included in the sixth part.

Part I. Preliminaries: Chapter 1 gives a brief description of the different kinds of PLL and reveals the weak points of the conventional PLL theory. These weak points arise from the dynamics of the controlled oscillator (VCO) and the ripple produced by the phase detector (PD), which are ignored in the conventional PLL theory.

Chapter 2 gives the description of the loop components (controlled oscillator, phase detector and low-pass filter) taking into account the saturation and the time delays that appear in the forward and the feedback paths of the loop. The controlled oscillator is represented by a parametric version of Liénard's equation. Liénard's equation is an almost complete non-linear model of the oscillators dominant dynamics.

Part II. First order PLL: Chapter 3 deals with the general behaviour of the first order PLL. Even though the first order loop is not of great practical importance, its investigation provides the physical interpretation of the PLL mechanism and gives considerable insight into the nonlinear behaviour of higher order loops. It is proven that synchronization is achieved through two actions: a control (regulation) and a parametric action, caused

[*] Nature enjoys hiding. Heraclitos

by the ripple. In addition, it is proven that any time delay appearing in the forward path of the loop does not affect the PLL performance.

Chapter 4 analyzes the main synchronization of the first order PLL. The analysis results in closed form expressions for the hold-in range, the tracking range, the lock-in time and the beat-note frequency. It is proved that the time delay in the feedback path causes a significant reduction of the main hold-in range. Furthermore, it is shown that the ripple causes an undesirable parametric resonance when the controlled oscillator is an almost harmonic oscillator. This resonance leads the PLL elements to saturation and destroys the analog behaviour of the loop.

Chapter 5 discusses the synchronization of the first order loop at the third harmonic of the center VCO frequency. It is proven that the harmonic synchronization is due to a parametric action of the ripple and it is independent of time delay. In addition, it is proved that in the absence of time delay the harmonic hold-in range is equal to the main hold-in range. However, in the presence of time delay the harmonic hold-in range is greater than the main hold-in range. This means that the harmonic (false) locking probability in the first order PLL is high.

Part III. Second order type-I PLL: Chapter 6 deals with the general behaviour of the widely used second order type-I PLL. In this loop a LPF is inserted between the PD and the VCO. The insertion of the LPF attenuates the ripple and alters the loop dynamics considerably.

Chapter 7 analyzes the synchronization of the second order type-I loop at the third harmonic of the VCO center frequency. The analysis provides the physical interpretation of the frequency acquisition procedure and clarifies the effect of the initial condition and the LPF in the dynamic behaviour of the loop.

Chapter 8 analyzes in depth the main synchronization of the second order type-I loop. The analysis results in closed form expressions for the hold-in, capture and tracking ranges, the lock-in time and the beat-note frequency. In addition, the analysis of this loop provides the physical interpretation of the fast (lock-in) and the slow (pull-in) capture procedure. Furthermore, new criteria for the optimum design of the loop are suggested.

Part IV. Second order type-II PLL: Chapter 9 treats the general behaviour of the second order type-II PLL. In this loop the LPF is replaced by a PI-controller. Type-II loops are considered to be superior to the type-I loops, especially due to their enlarged capture and tracking ranges. However, the loop suffers from the saturation of the PI-controller, caused by the ripple. To avoid saturation, the analog gain of the PI-controller should be low. With a low analog gain the lock-in time increases considerably.

The saturation splits the hold-in range in two parts: the unsaturated and the saturated hold-in range. In the unsaturated hold-in the steady state phase error between the reference and the VCO signal is equal either to zero or to $\pi/2$. In contrast, in the saturated hold-in range this error becomes a function of the reference frequency and the loop behaves as a first order one.

Chapter 10 analyzes the main synchronization of the second order type-II PLL. This analysis results in closed form expressions for the hold-in range, the tracking range and the lock-in time of the unsaturated loop. Furthermore, the stability criteria of the loop are stated.

Chapter 11 analyzes briefly the synchronization of the second order type-II loop at the third harmonic of the VCO center frequency. It is proved that the harmonic hold-in range is large and depends strongly on initial conditions and on the analog gain of the PI-controller.

Part V. Third order type-II PLL: Chapter 12 discusses the general behaviour of the third order type-II PLL. In this loop a LPF is inserted between the PD and the PI-controller. The LPF reduces the ripple and the saturation of the PI-controller is prevented.

Chapter 13 treats the main synchronization of the third order type-II PLL. The analysis results in closed form expressions for the hold-in range, the tracking range and the lock-in time of the unsaturated loop. Furthermore, the stability problem of this loop is detected and new criteria for the loop design are stated.

Chapter 14 examines briefly the synchronization of the third order type-II loop at the third harmonic of the VCO center frequency. It is proved that the harmonic hold-in range is small compared with the main hold-in range.

The material contained in this book is the outcome of theoretical and experimental research efforts that lasted for many years. I hope that it will prove useful through suggesting new techniques in the analysis and synthesis of phase locked loops.

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Thessaloniki, December 2003 *Nikolaos I. Margaris*